TESTING BARYOGENESIS WITH FUTURE COLLIDERS

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Based on
David Curtin, PM, Chiu-Tien Yu 1408.xxxx

WHERE DO WE GO FROM HERE?

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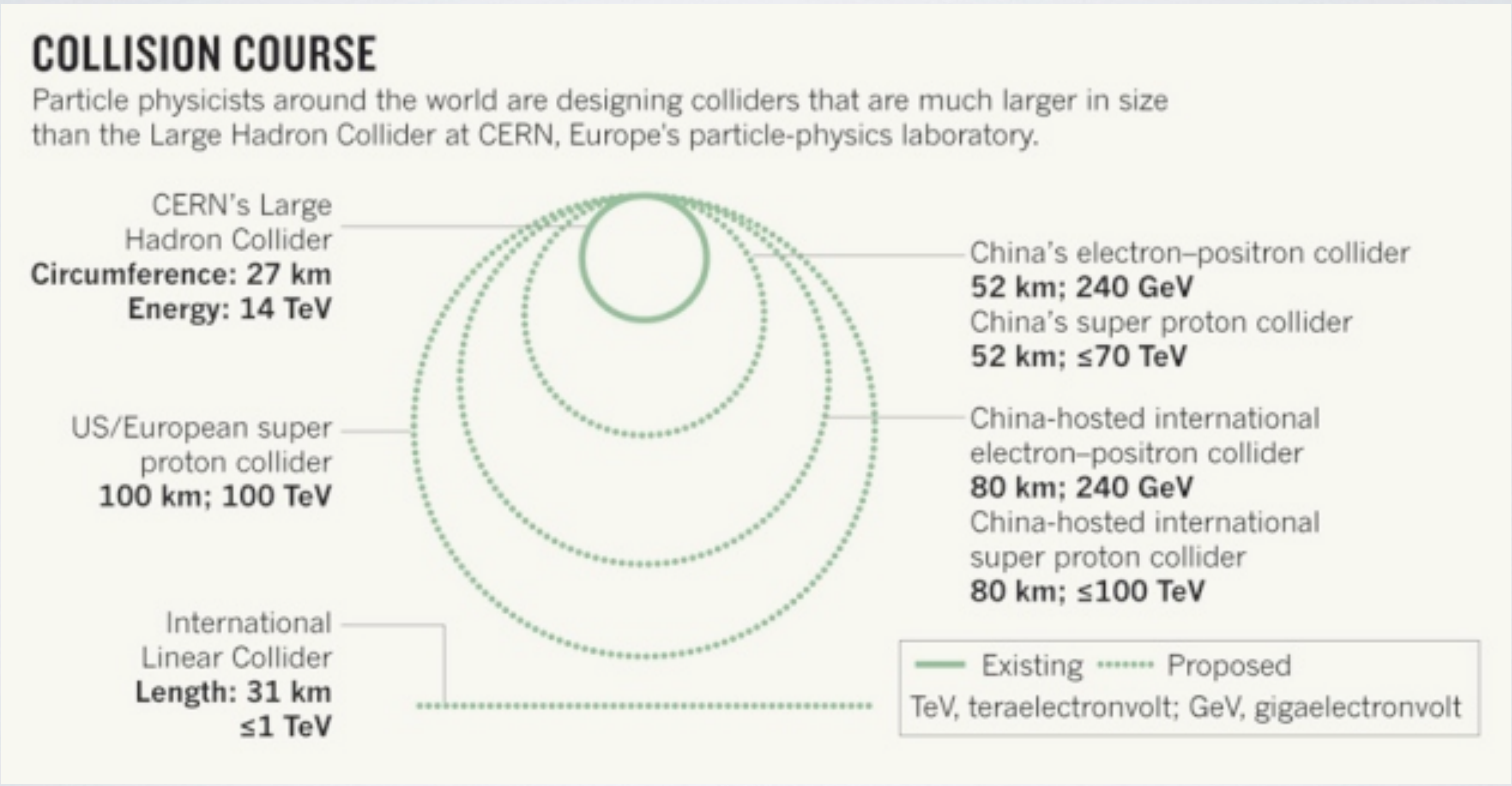

IT'S DIFFICULT TO SAY…

- Depending on the physics question you want to answer you may try to go with different strategies for finding new physics, e.g. total Higgs width versus finding new states

- Generically ***bigger*** is ***better!***

THE PROBLEM WITH THE BIGGER IS BETTER STRATEGY…

When is bigger big enough???

Naturalness, Dark Matter, Stability of our Universe point to what scale?

Are there questions that can definitively be wrapped up?
Are there unambiguous physics questions that can be answered with a BIG collider?

WE WANT A PROBLEM UNAMBIGUOUSLY TIED TO A “LOW” SCALE AND WITH SIGNIFICANT IMPLICATIONS

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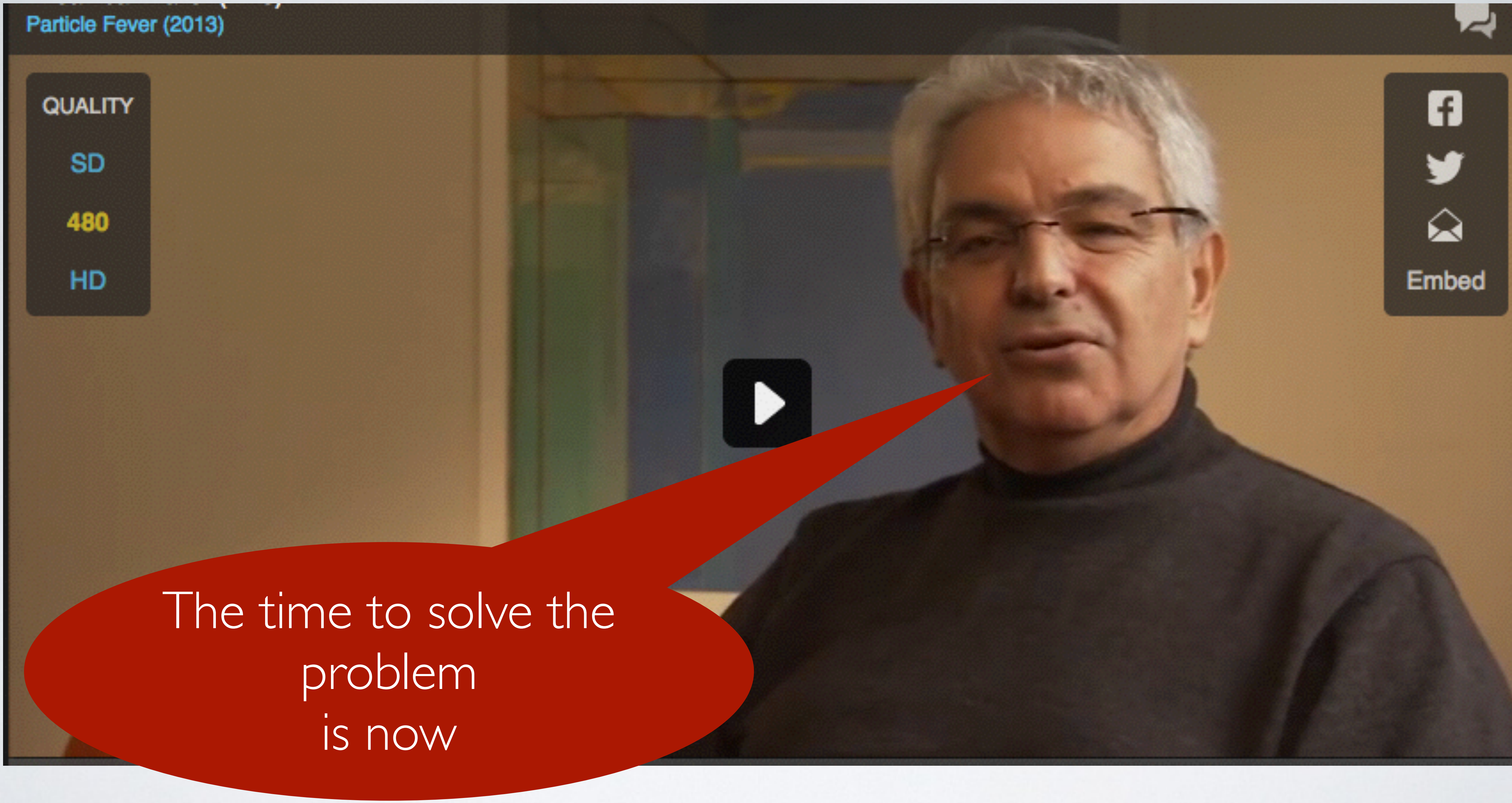
* And ***not*** just buzz words attached to things like CP violation in neutrinos implying it has ***anything*** to do with the Matter-Antimatter asymmetry observed

OR ANOTHER WAY OF SAYING IT…



WE WANT A PROBLEM UNAMBIGUOUSLY TIED TO A "LOW" SCALE AND WITH SIGNIFICANT IMPLICATIONS

ELECTROWEAK BARYOGENESIS

BARYOGENESIS

$$2.6 \times 10^{-10} < \eta \equiv \frac{n_b - n_{\bar{b}}}{s} < 6.2 \times 10^{-10}$$

- Many ideas out there
  - Leptogenesis
  - Affleck-Dine
  - Tying Dark Matter and Baryon Asymmetry
  - GUT Baryogenesis
  - Electroweak Baryogenesis… Could have been the easiest option, and still may be true! Can we make **sharp** statements?

ELECTROWEAK BARYOGENESIS

$$2.6 \times 10^{-10} < \eta \equiv \frac{n_b - n_{\bar{b}}}{s} < 6.2 \times 10^{-10}$$

- Sakharov conditions
  - B violation **(already in SM: Sphalerons)**
  - CP violation **(already in SM: obvious...)**
  - departure from thermal equilibrium **(already in SM: EW phase transition)**

ELECTROWEAK BARYOGENESIS

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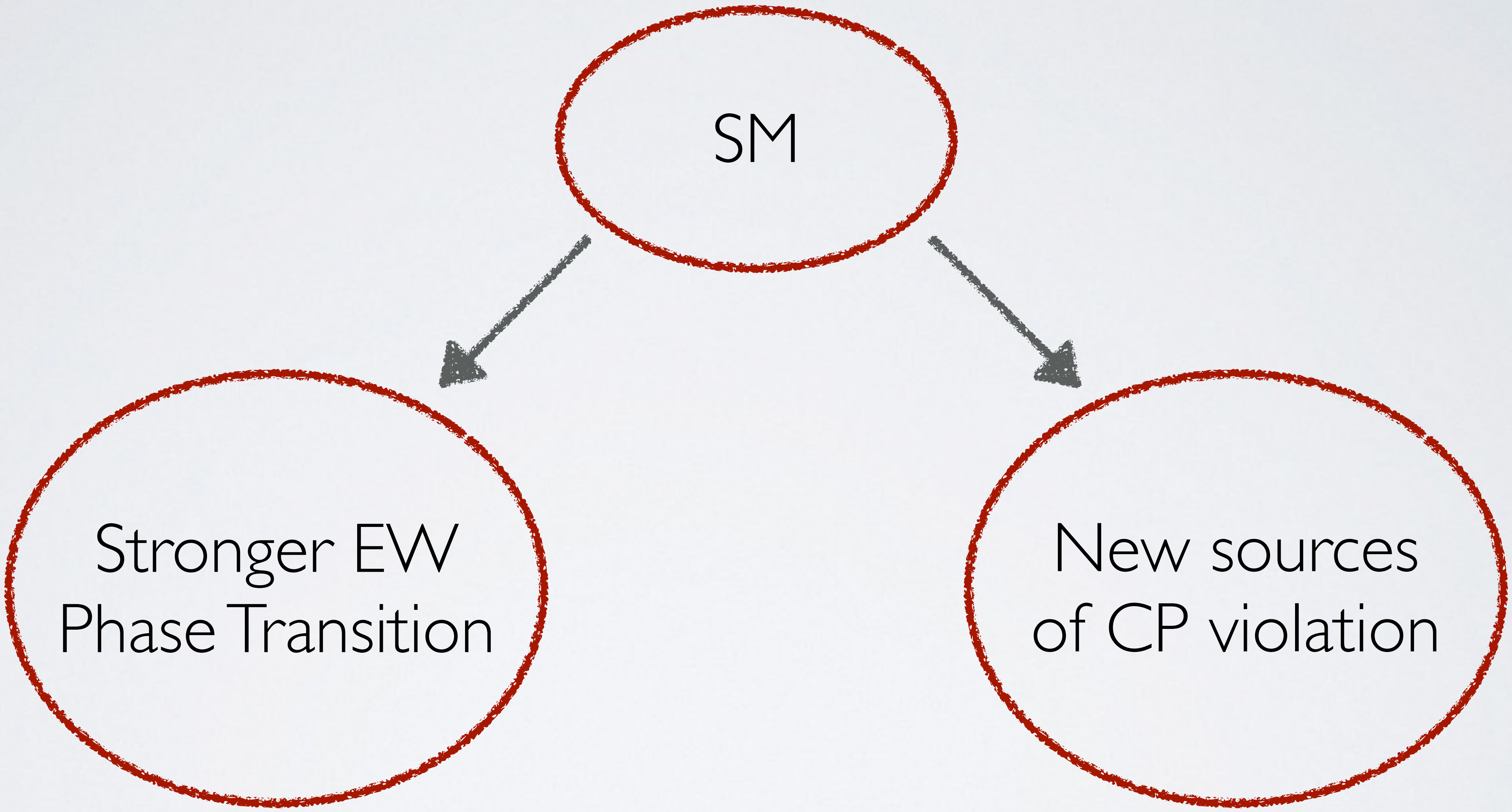
Alas not enough of these in SM

HOW DOES THE SM NEED SUPPLEMENTED TO MAKE EWBG WORK?



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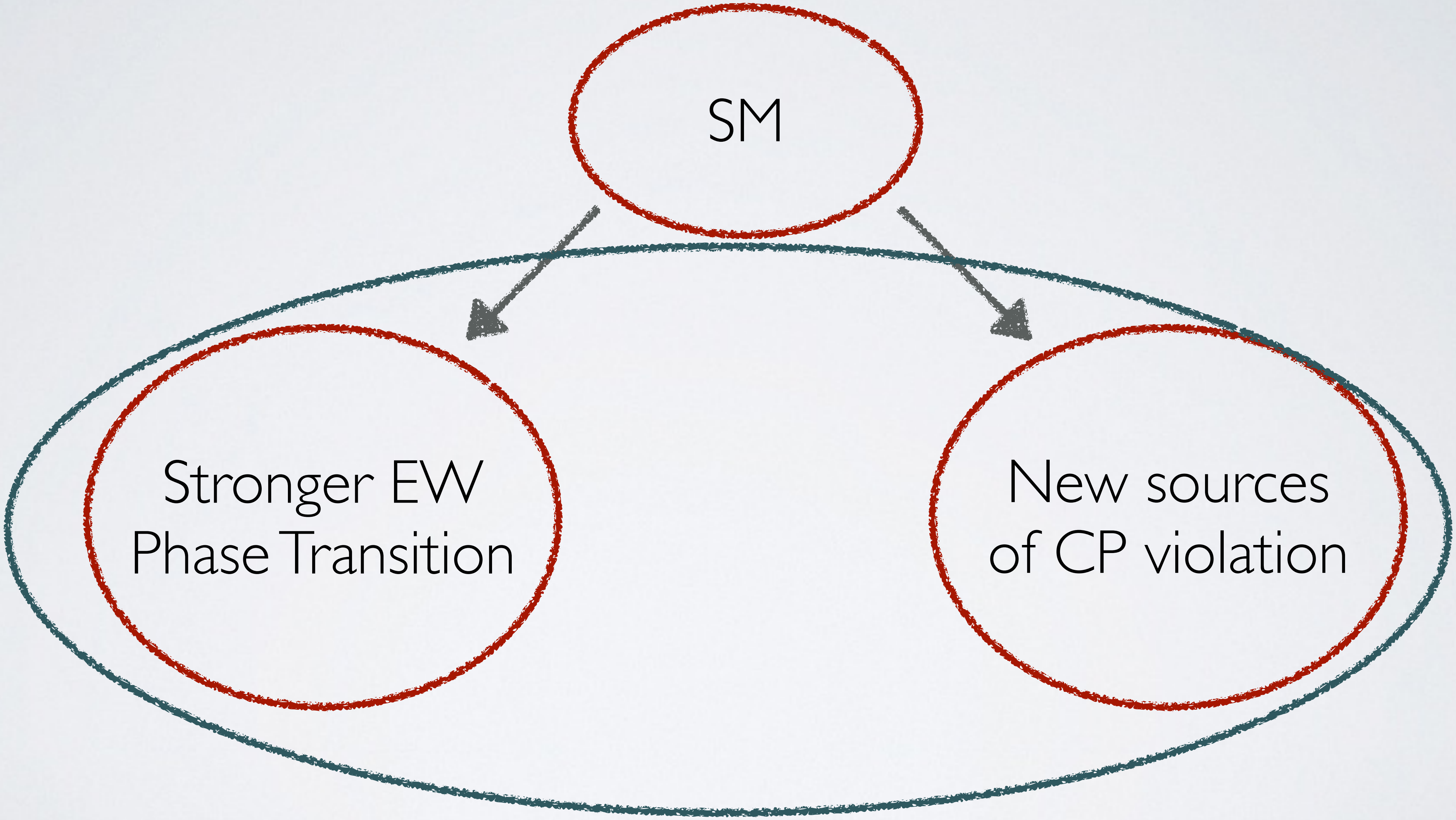
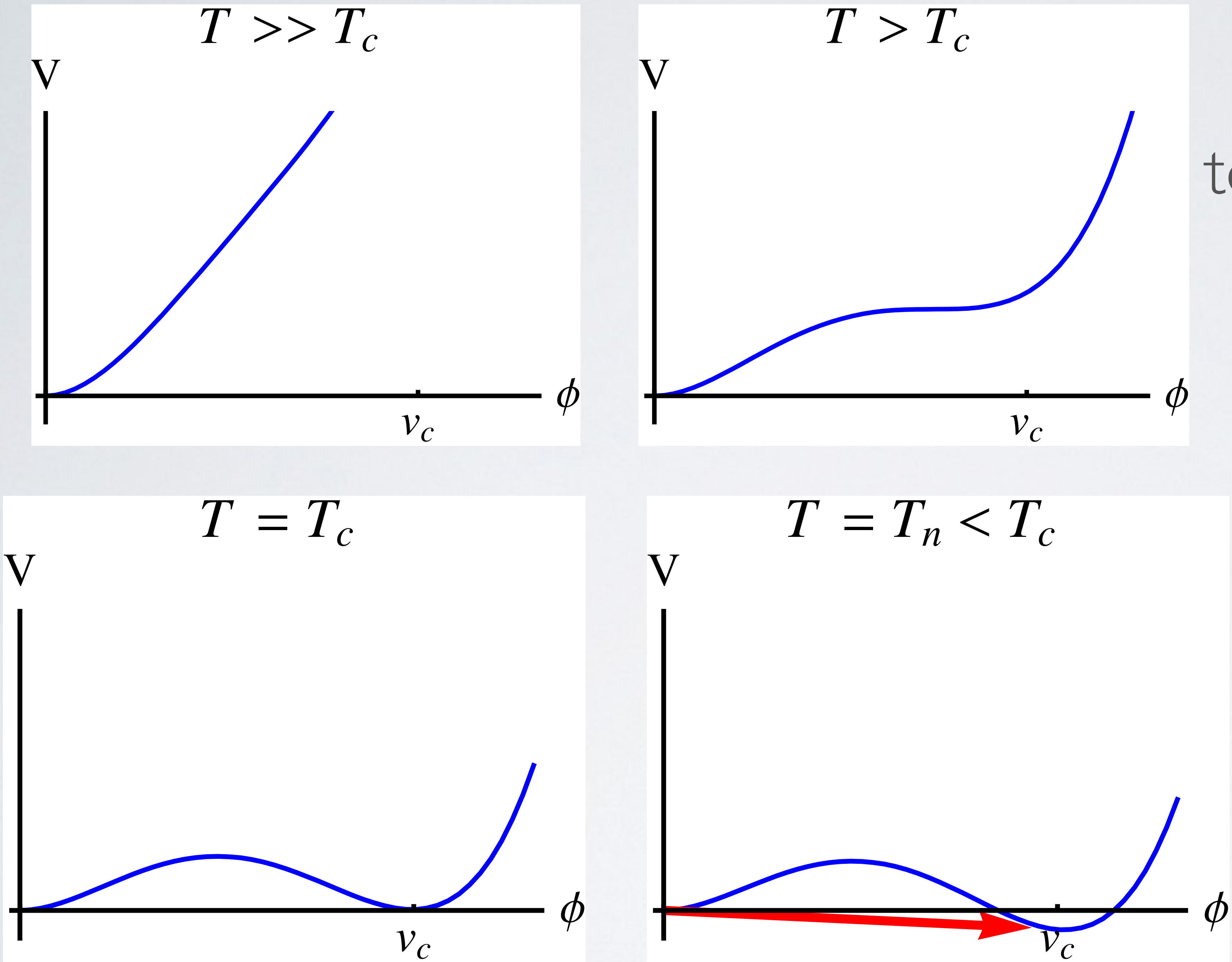


Often times a complete model has both, e.g. the MSSM
What do they mean in practice?

EW PHASE TRANSITION



We need the full thermal potential to have a strong 1st order phase transition

$$\frac{\langle\phi\rangle}{T_c} \sim 1$$

This translates in the Higgs potential to

$$\frac{\langle\phi\rangle}{T_c} \sim \frac{cubic}{quartic}$$

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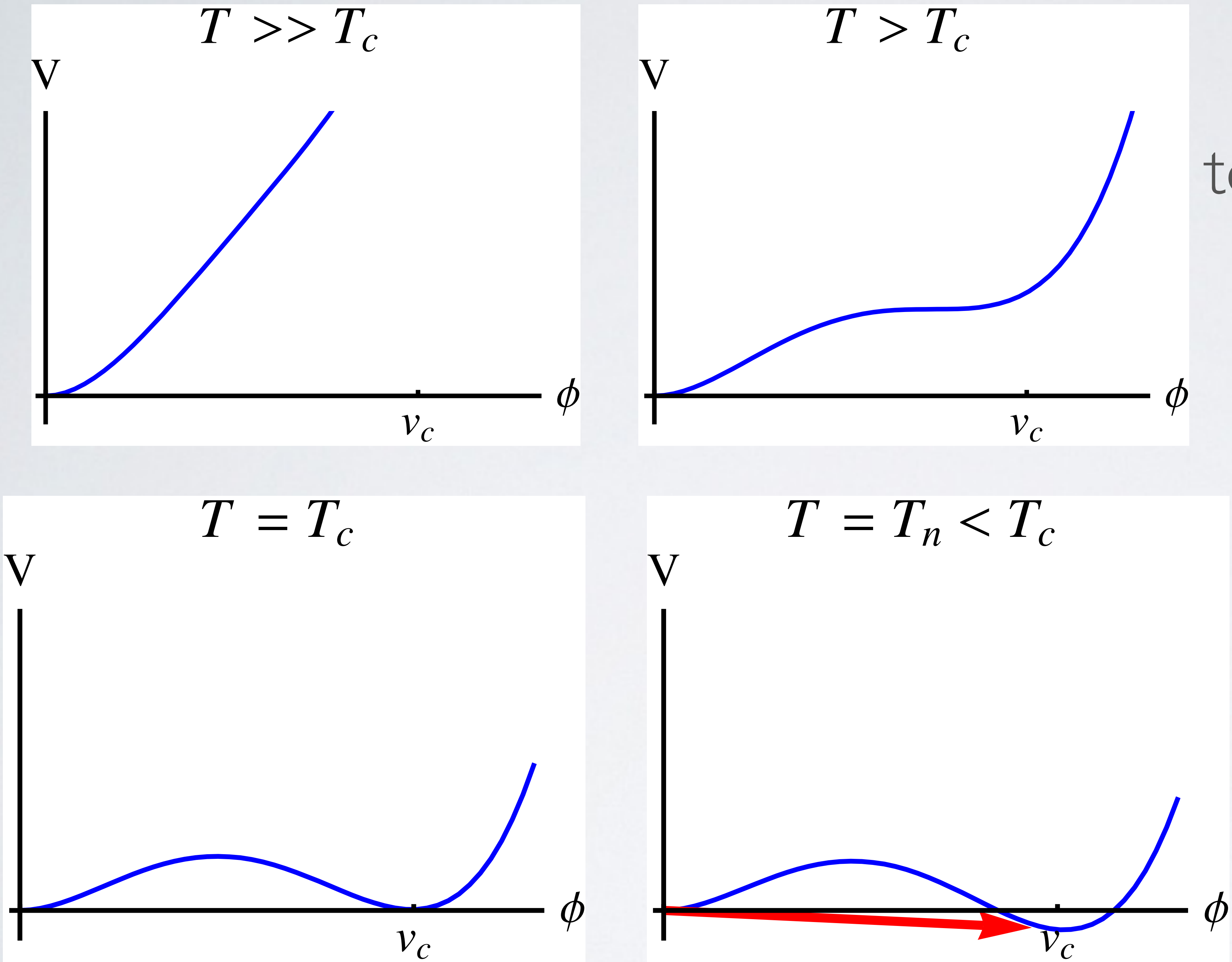

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Bottom line something new has to couple to the Higgs strongly!!

FACTORIZED EWBG

Out of Eq. Calculation

Straightforward

$$\frac{\langle \phi(T_c) \rangle}{T_c} \gtrsim 1$$

Baryon Asymmetry Calculation

Harder

tunneling,
quantum transport,
hydrodynamics

FACTORIZED EWBG

1st order phase transition

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Straightforward

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New sources of CP violation

Baryon Asymmetry Calculation

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FACTORIZED EWBG

There can be factorized ways to test this for instance in the MSSM

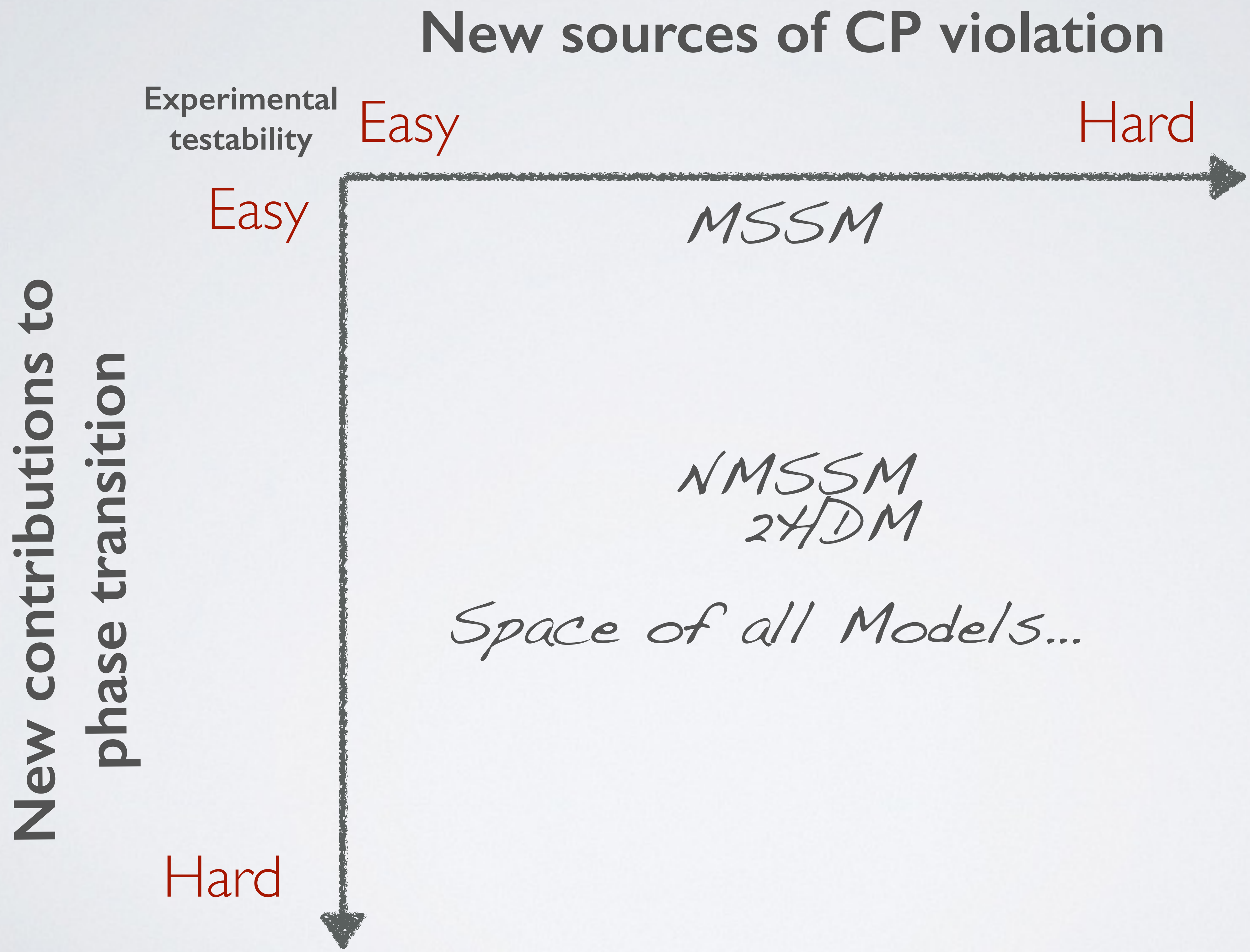
1st order phase transition	New sources of CP violation
Higgs couplings	EDMs
MSSM requires a light stop ~ 100 GeV	

THE FACTORIZED SEARCH FOR EWBG HAS WORKED BEFORE…

- Factorized search doesn't **confirm** EWBG but can **disprove** or provide the direction for proving! (important for knowing how far to go…)

- Can we extend this basic idea of searching for things that modify the phase transition, and add to CP violation to cover all ideas of EWBG and with new colliders??… Maybe! (building evidence…)

WHERE TO LOOK WITHOUT HAVING A MODEL INDEPENDENT FORMULATION



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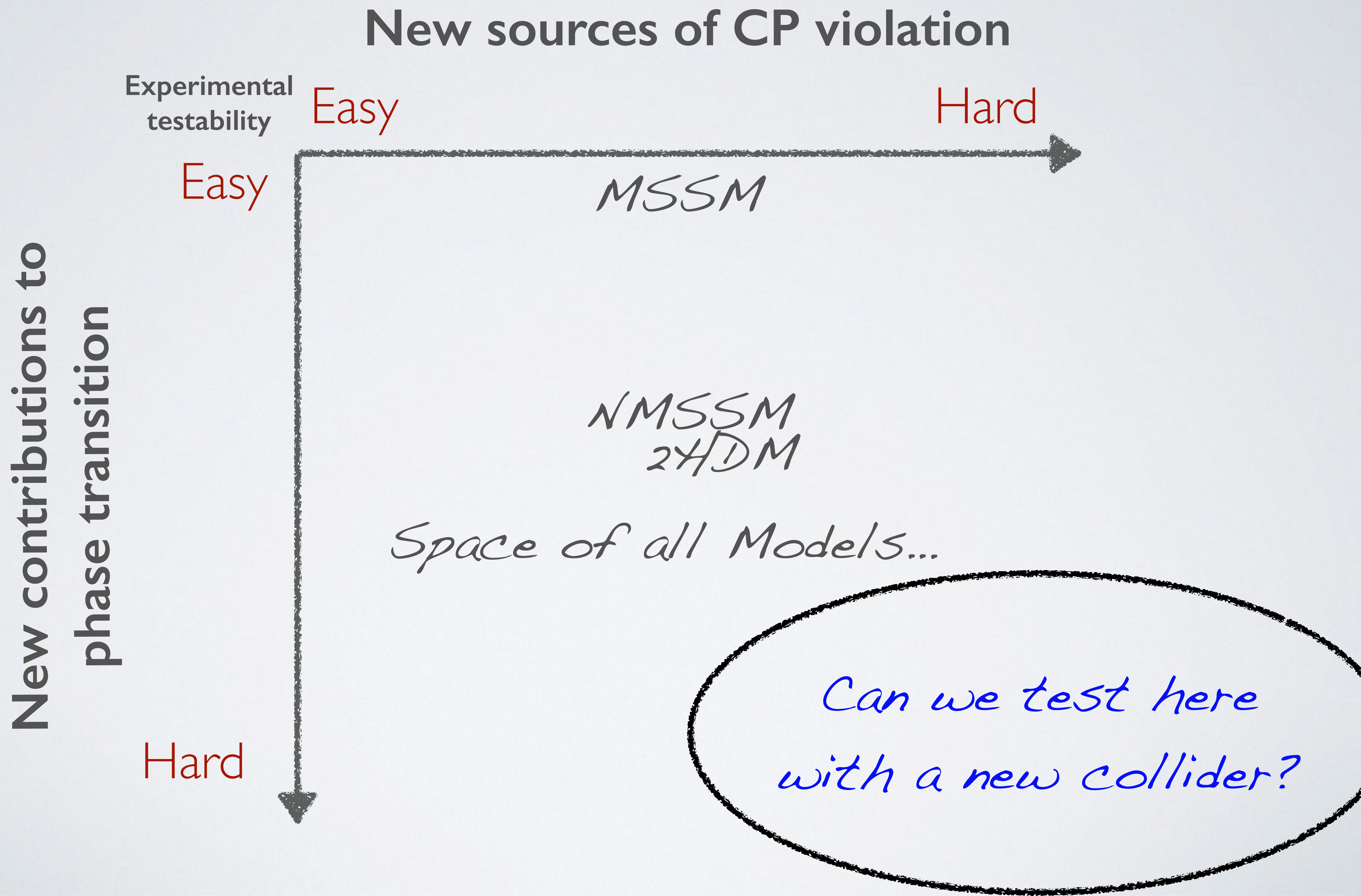

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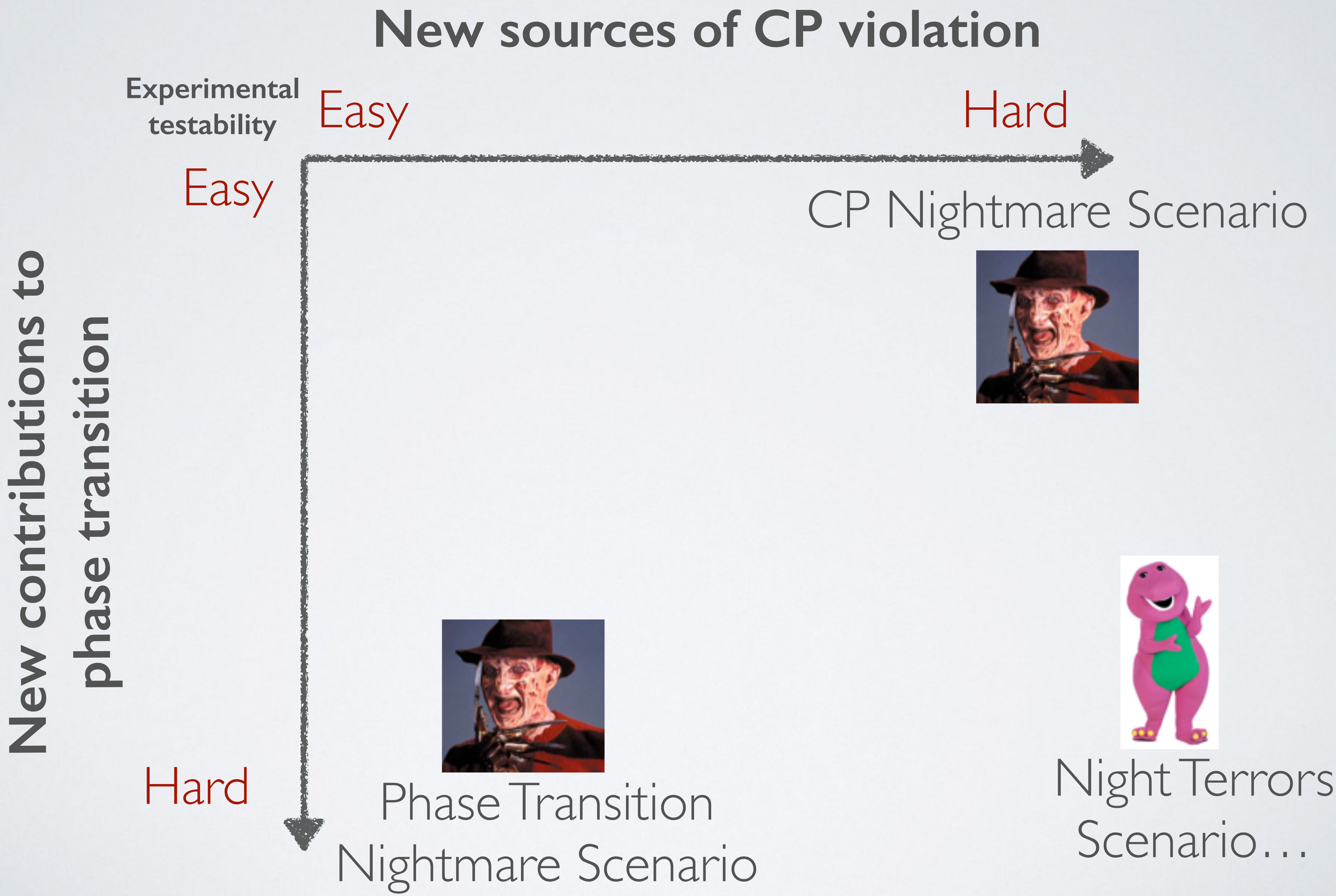

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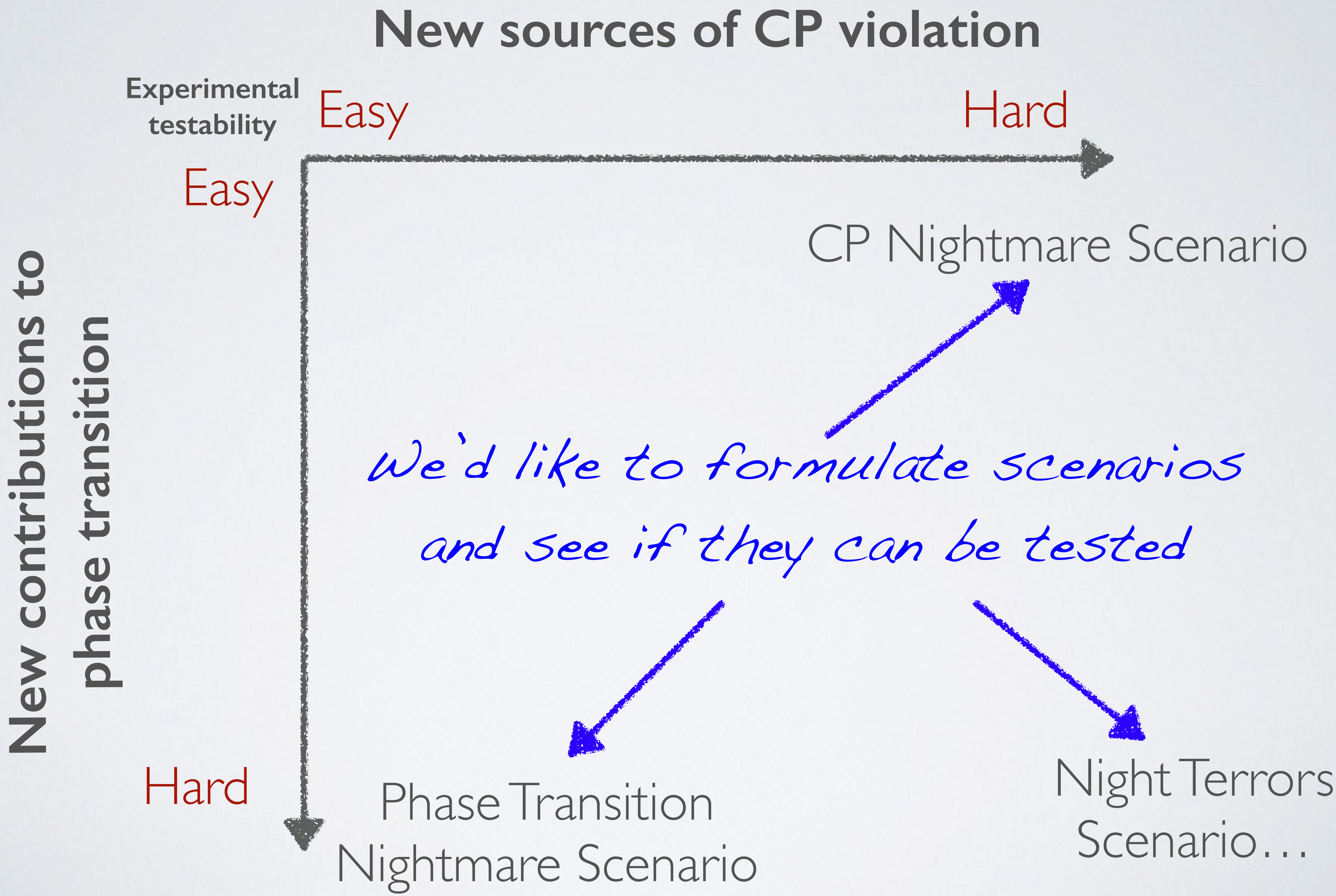


PHASE TRANSITION NIGHTMARE SCENARIO

- Categorization of new physics that can contribute to the phase transition have been thought about, see for instance 1209.1819 by Liantao et al.

- We'd like to look at a simple model for enhancing the phase transition that has been explored numerous times, but take it into a perverse limit that makes it extremely hard to see…

SM + SINGLET

This scenario has been studied numerous times for a variety of reason….

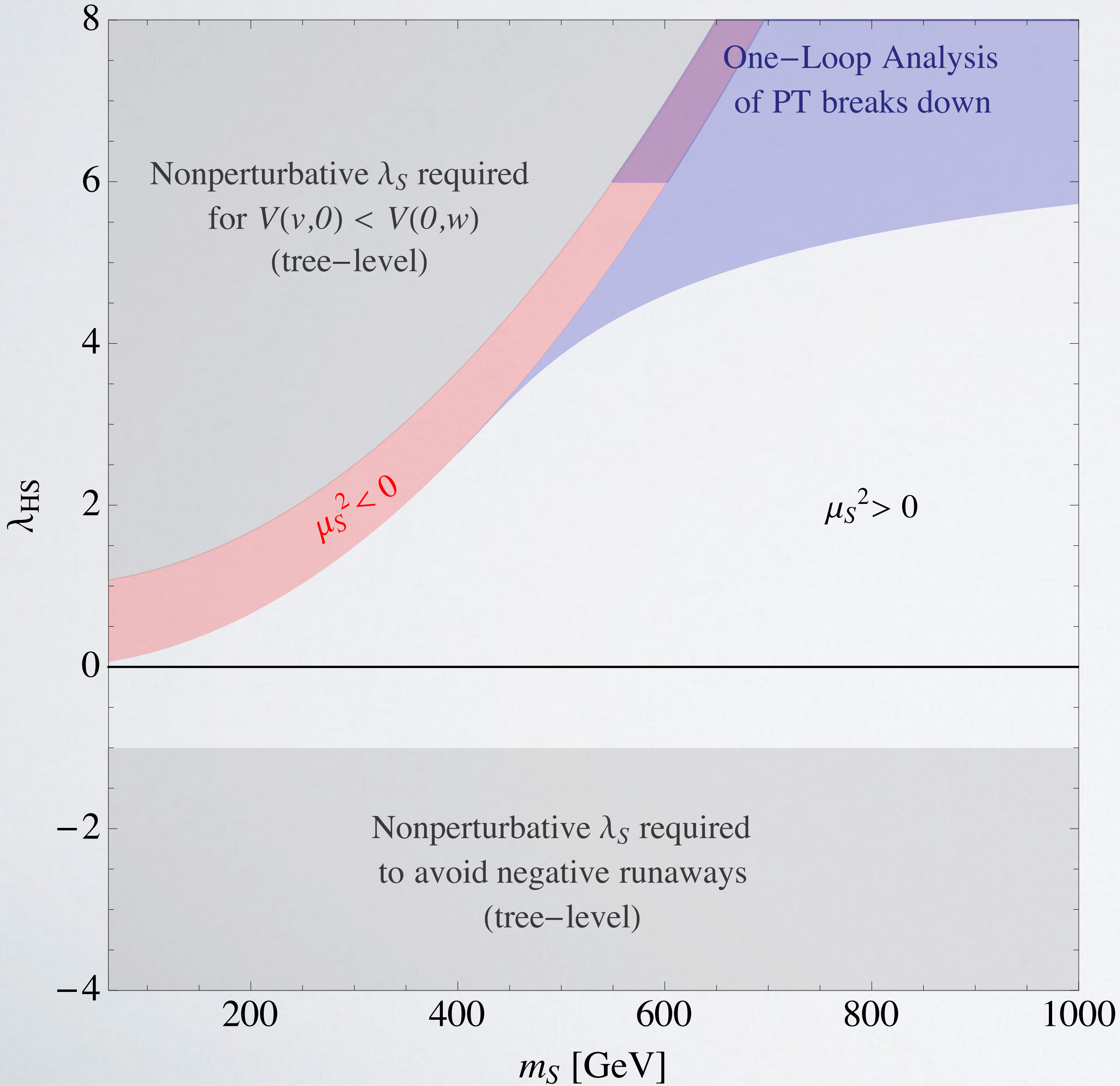
If the Singlet mixes with the Higgs you can see it easily via Higgs properties and has been studied quite a bit

If the Singlet DOESN'T mix but its mass is less than half the Higgs mass you can see it in decays easily…

What if the singlet doesn't mix with the Higgs and is heavy?

SM + SINGLET NIGHTMARE SCENARIO

$$V_0 = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{HS} h^2 S^2 + \frac{1}{4}\lambda_S S^4$$



$$m_S^2 = \mu_S^2 + \lambda_{HS} v^2 > 0$$

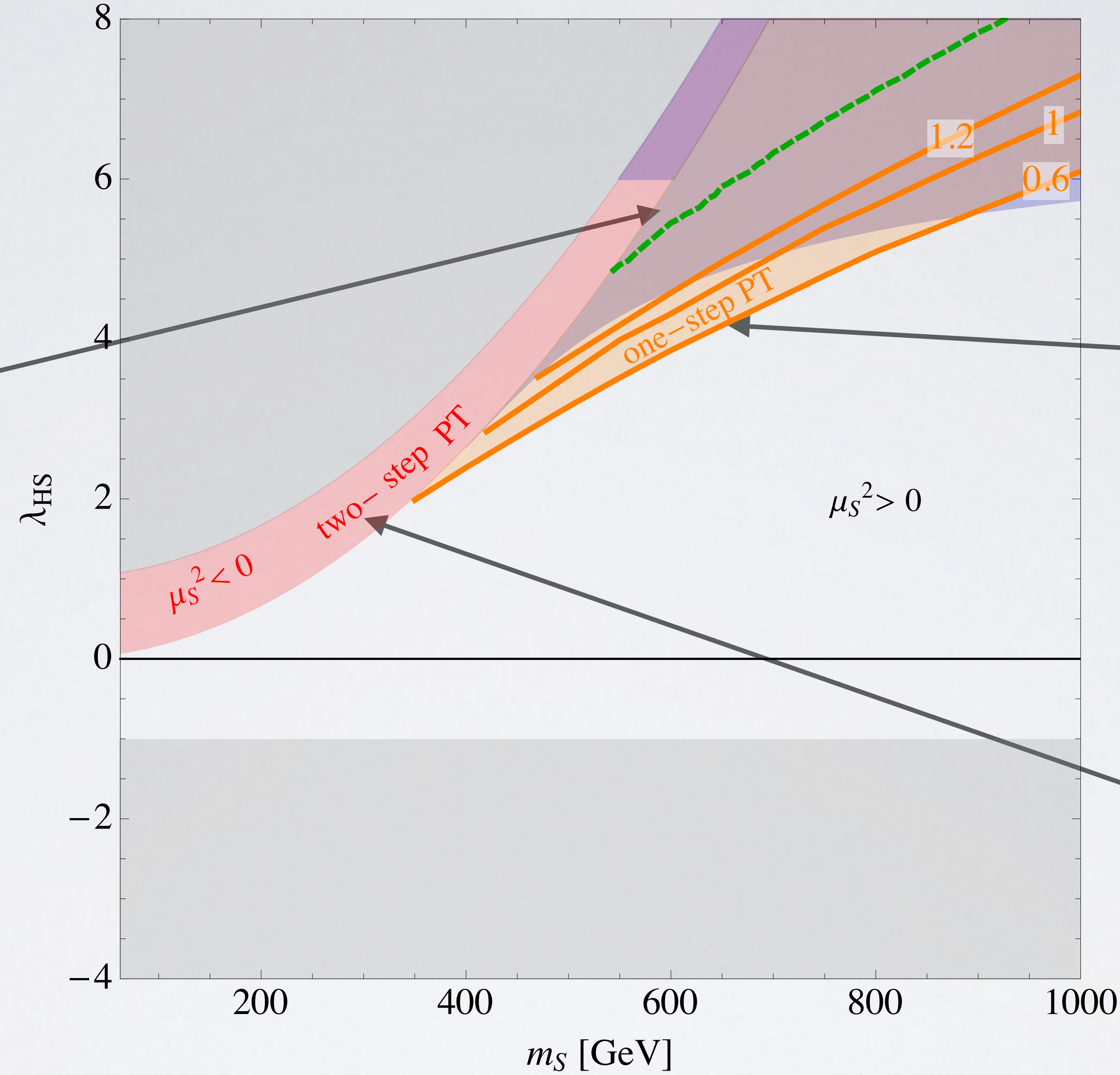
Phenomenological parameter space depends only on

$$(m_S, \lambda_{HS})$$

There are two qualitatively different regions depending on the sign of μ_S^2

WHERE IN THE PARAMETER SPACE IS THERE A GOOD PHASE TRANSITION?

thin sliver with thermal 1-step PT



1-step PT zero T loops

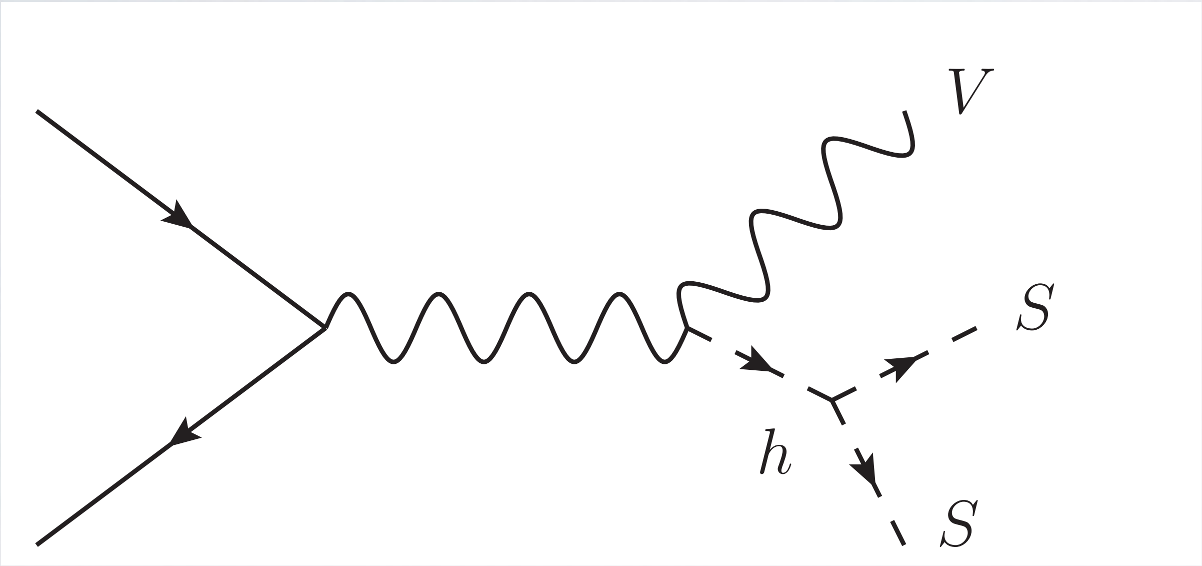
2-step PT transition

Figure 3. Regions in the (m_S, λ_{HS}) plane with viable EWBG. Red shaded region: for $\mu_S^2 < 0$ it is possible to choose λ_S such that EWBG proceeds via a tree-induced strong two-step electroweak phase transition. Orange contours: value of v_c/T_c for $\mu_S^2 > 0$. The orange shaded region indicates $v_c/T_c > 0.6$, where EWBG occurs via a loop-induced strong one-step phase transition. Above the green dashed line, singlet loop corrections generate a barrier between $h = 0$ and $h = v$ even at $T = 0$, but results in the dark shaded region might not be reliable, see Section 3.1.3.

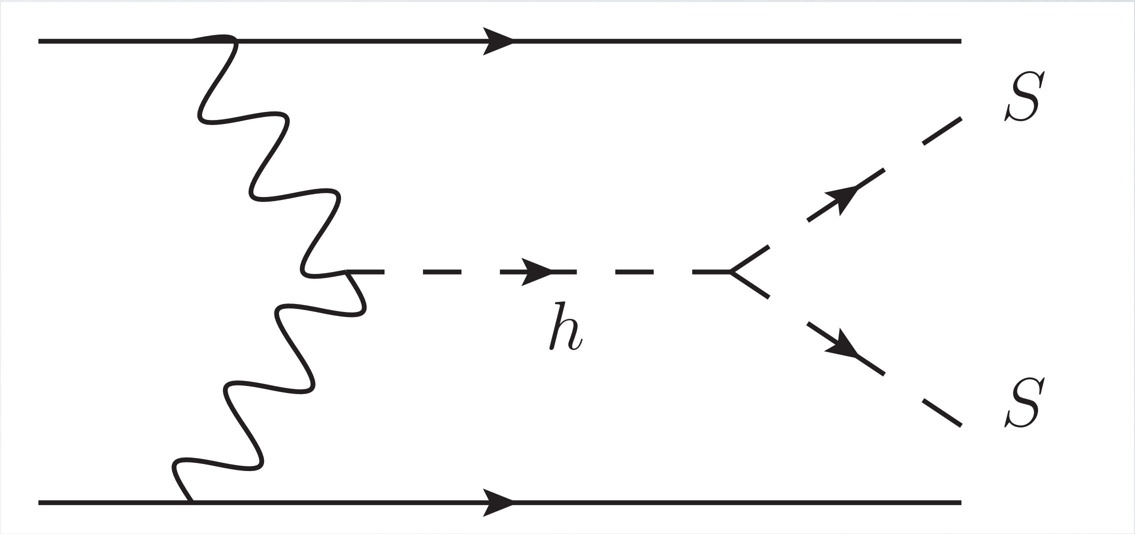
HOW DO WE SEE SUCH A THING?

- Directly make S
- Indirectly probe triple Higgs coupling in di-Higgs production
- Indirectly probe through Zh coupling

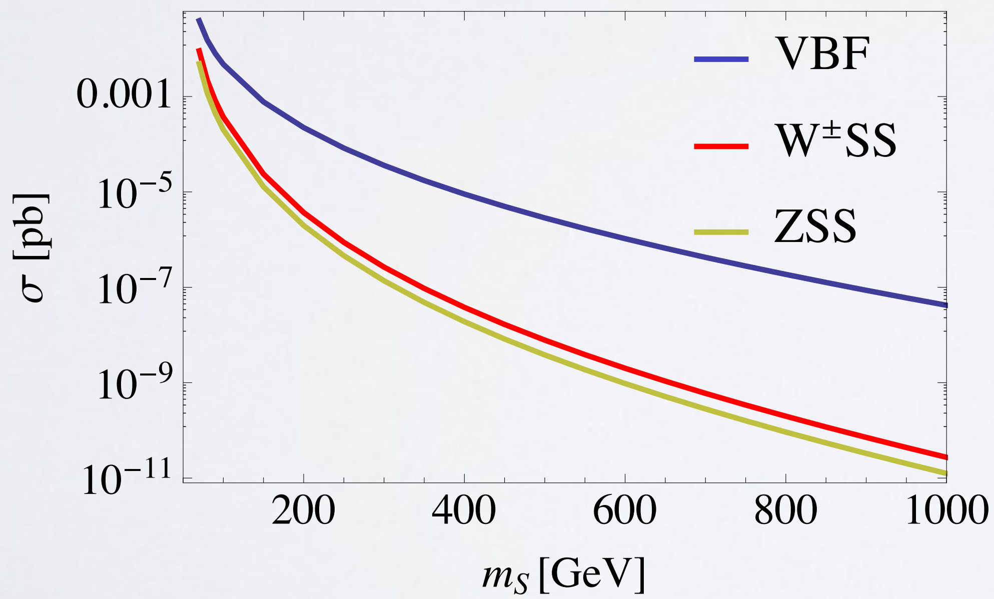
DIRECT PRODUCTION OF SINGLETS



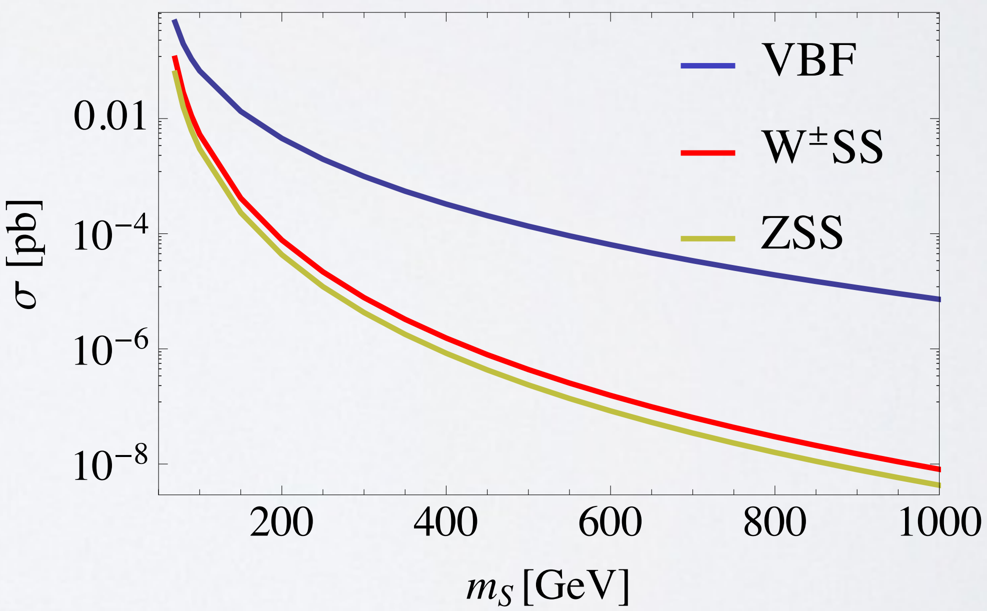
(a) Associated Production



(b) Vector Boson Fusion



(a) 14 TeV



(b) 100 TeV

Figure 7. Production cross-sections at hadron colliders for various modes of singlet production with $\lambda_{HS} = 2$. These calculations were computed at LO with MadGraph5 [84]

POTENTIAL REACH...

Toy VBF study, using Snowmass backgrounds and detectors

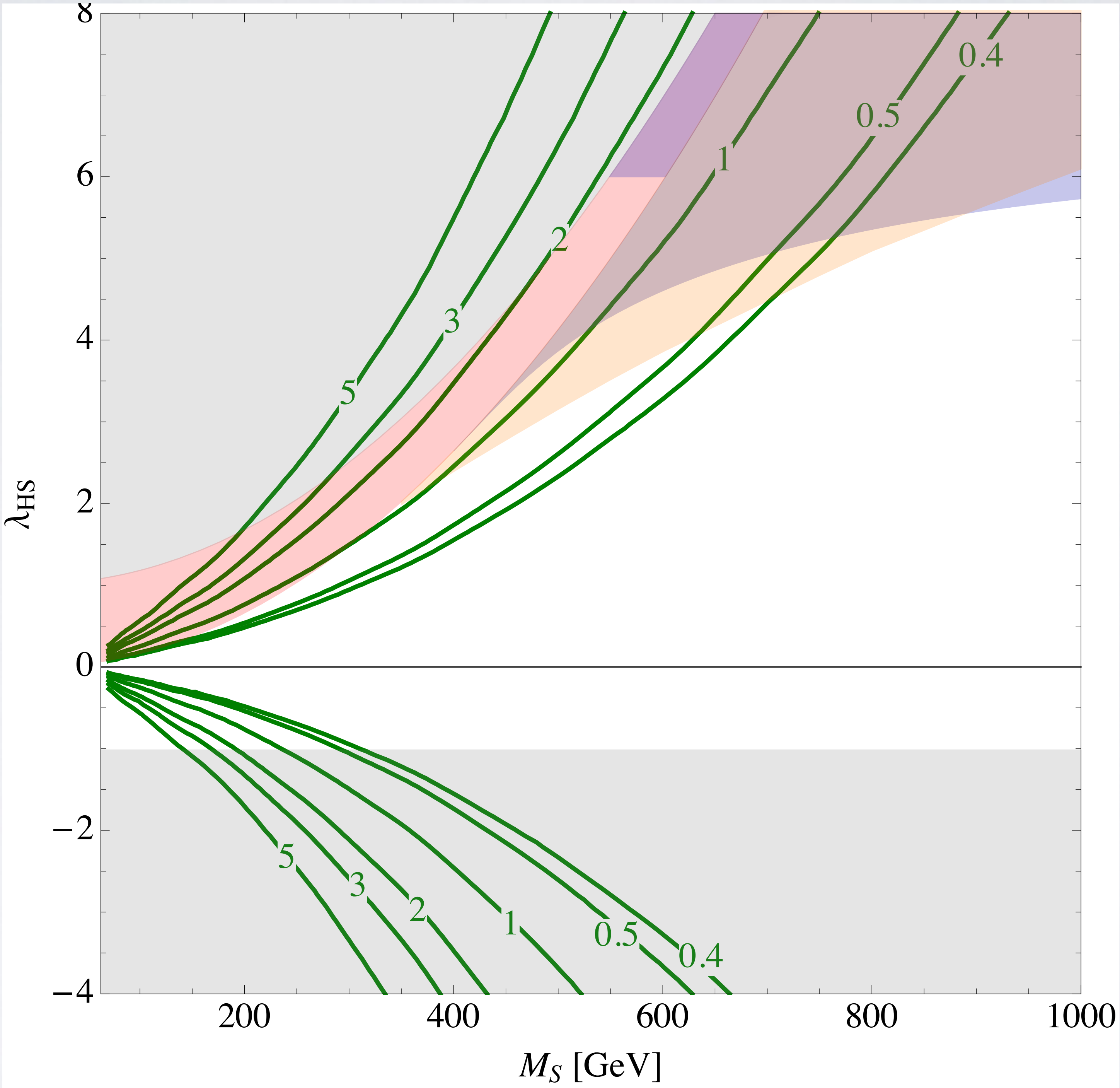
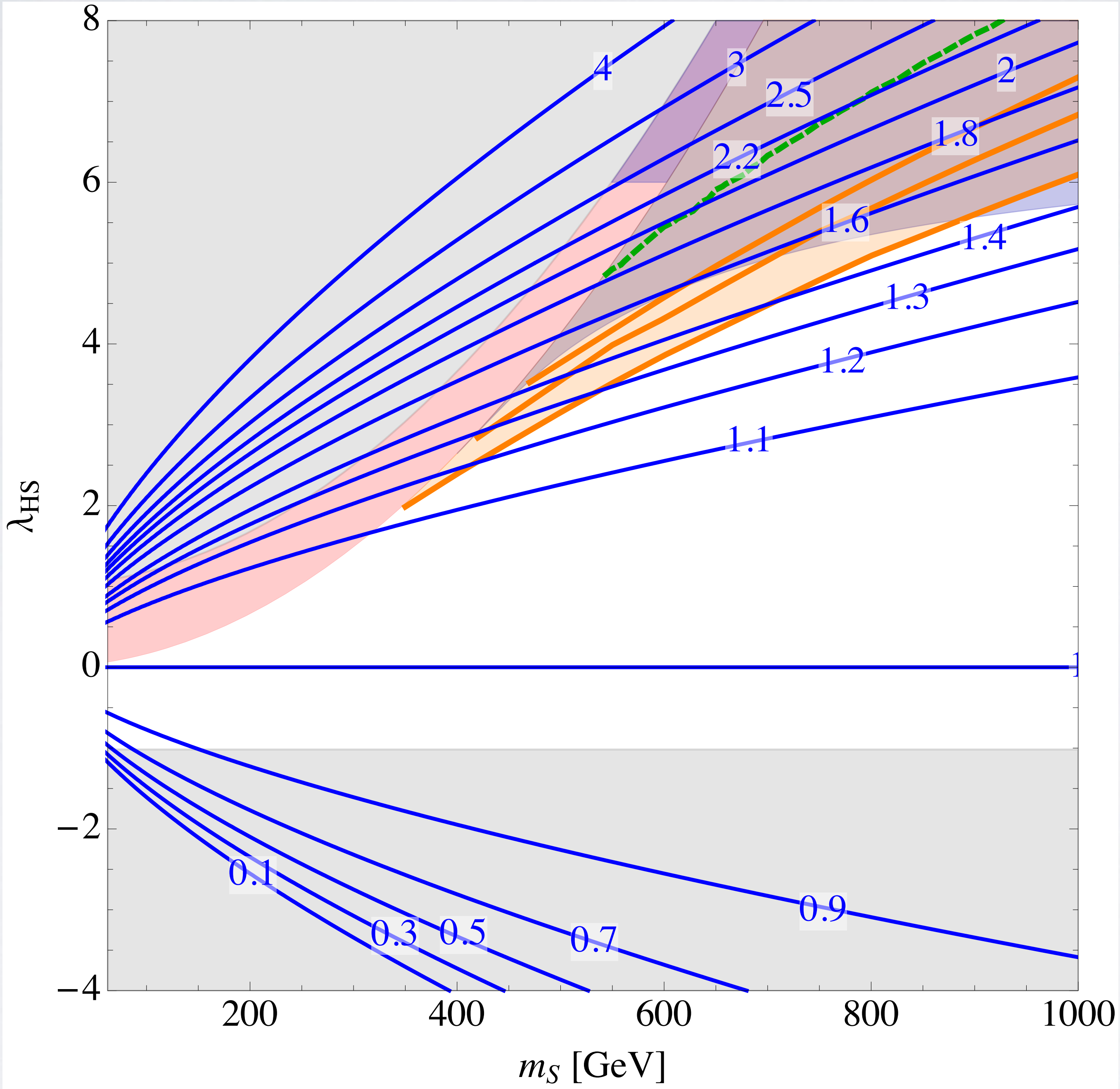


Figure 8. Dark green contours show $S/\sqrt{B}$ for VBF production of the $SSqq$ signal vs the main background, VBF production of $Z \to \nu\bar{\nu}$, for a 100 TeV pp collider with 3000 fb^{-1} of data. We use VBF selection criteria with a requirement that $\not{E}_T > 150$ GeV to cut down on QCD background. Shading identical to Figs. 3 and 5.

TRIPLE HIGGS COUPLING PROBES



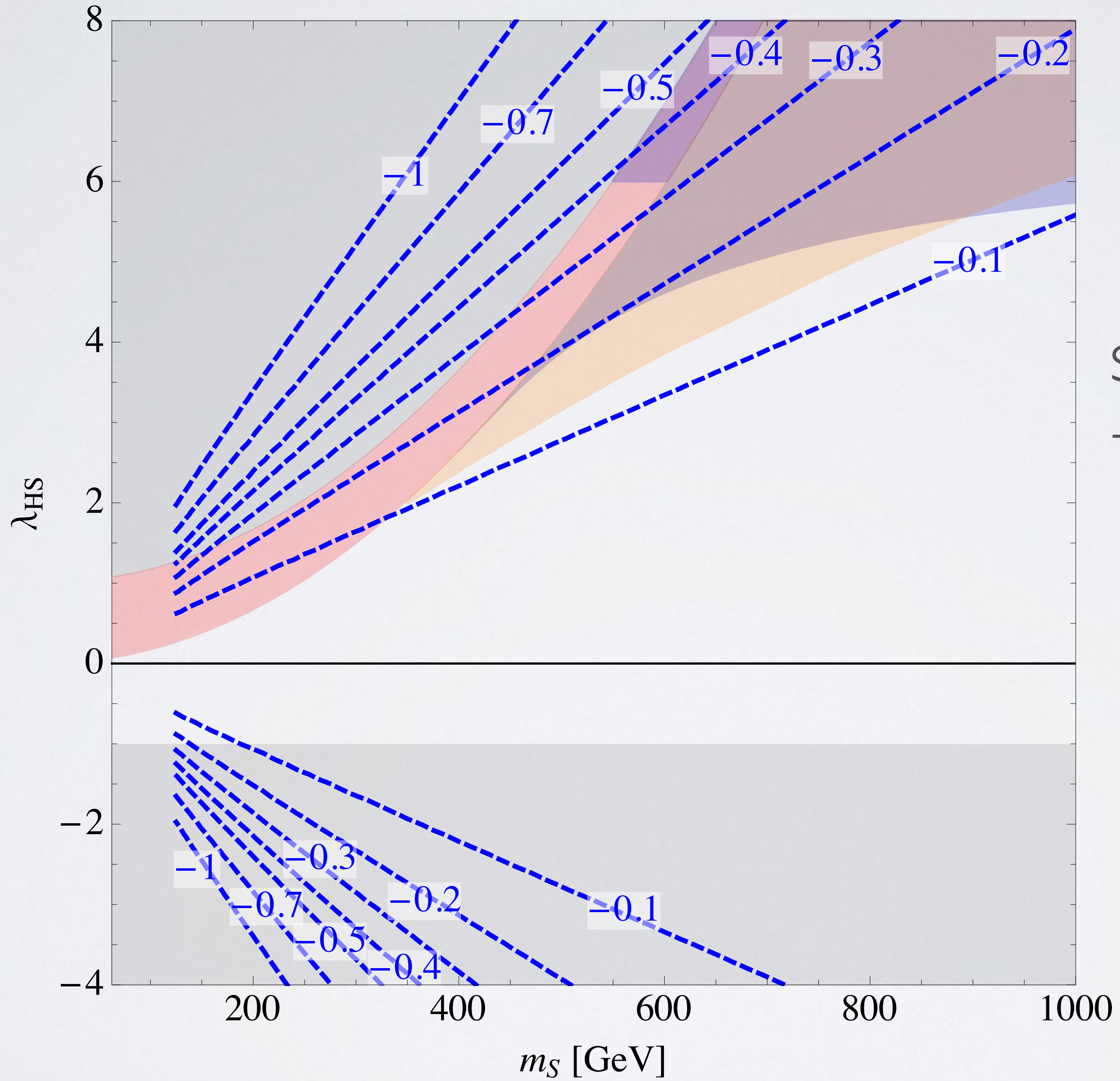
Triple Higgs probes are ***extremely*** important!!!!

We must get these estimates correct and double checked for any future collider

Figure 9. The thin blue lines map out the contours of $\lambda_3/\lambda_3^{\rm SM}$. Accuracies of 30%, 20%, and 8% can be achieved at 14 TeV, 33 TeV, and 100 TeV hadron colliders with 3 ab^{-1} of data, respectively. A 1000 GeV ILC with 2.5 ab^{-1} could achieve a precision of 13%. See text for details.

ZH TRIPLE HIGGS PROBES

e.g. N. Craig, C. Englert, M. McCullough 1305.5251



Recent studies suggest a measurement to O(.5)% so it doesn't compete with di-Higgs measurement of triple Higgs shifts

Figure 12. Dashed blue contours: the one-loop corrections to the associated production cross-section of Zh at lepton colliders Eq. (5.2), in % relative to the SM.

DARK MATTER! (MORE COMPLEX THAN NORMAL)

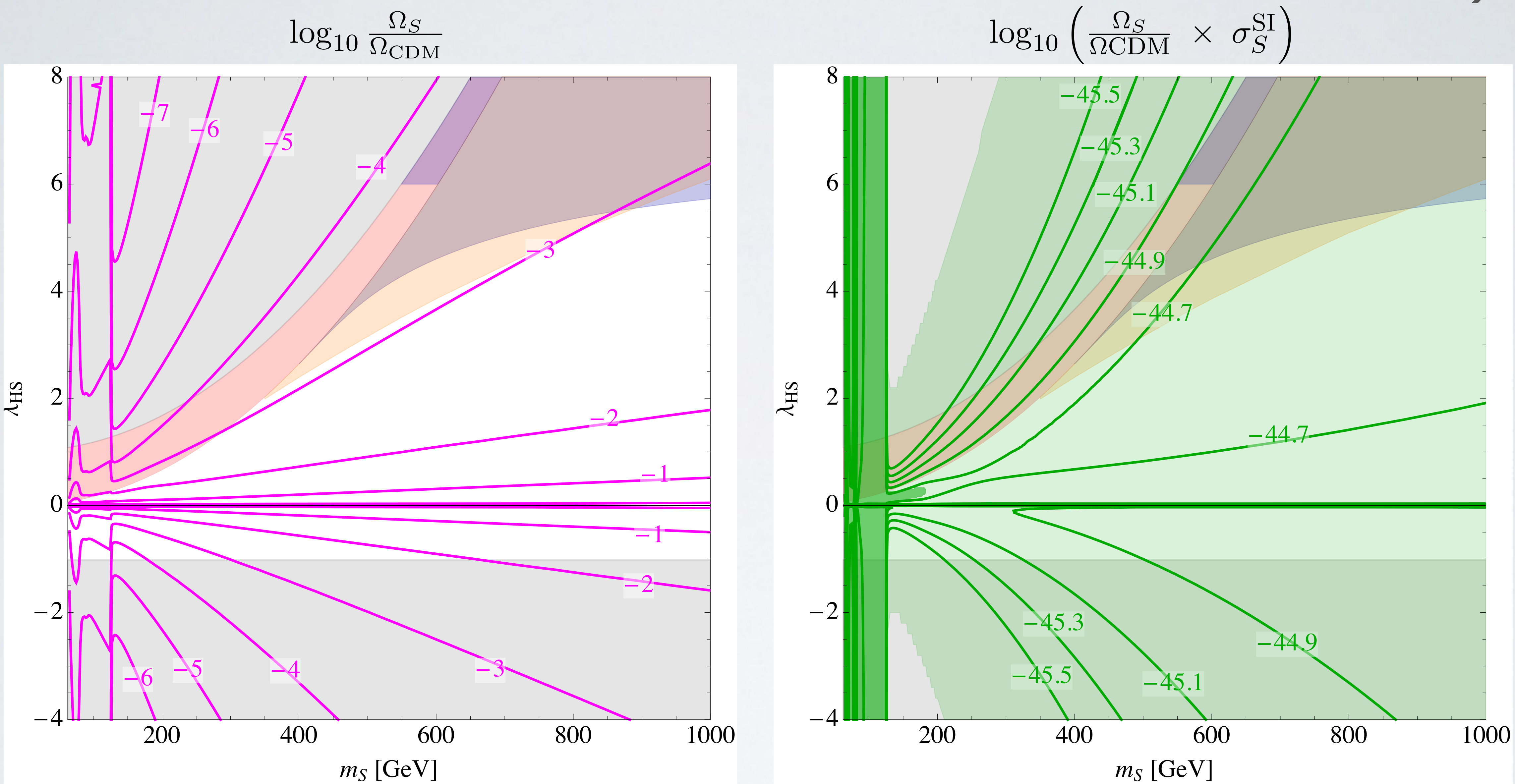
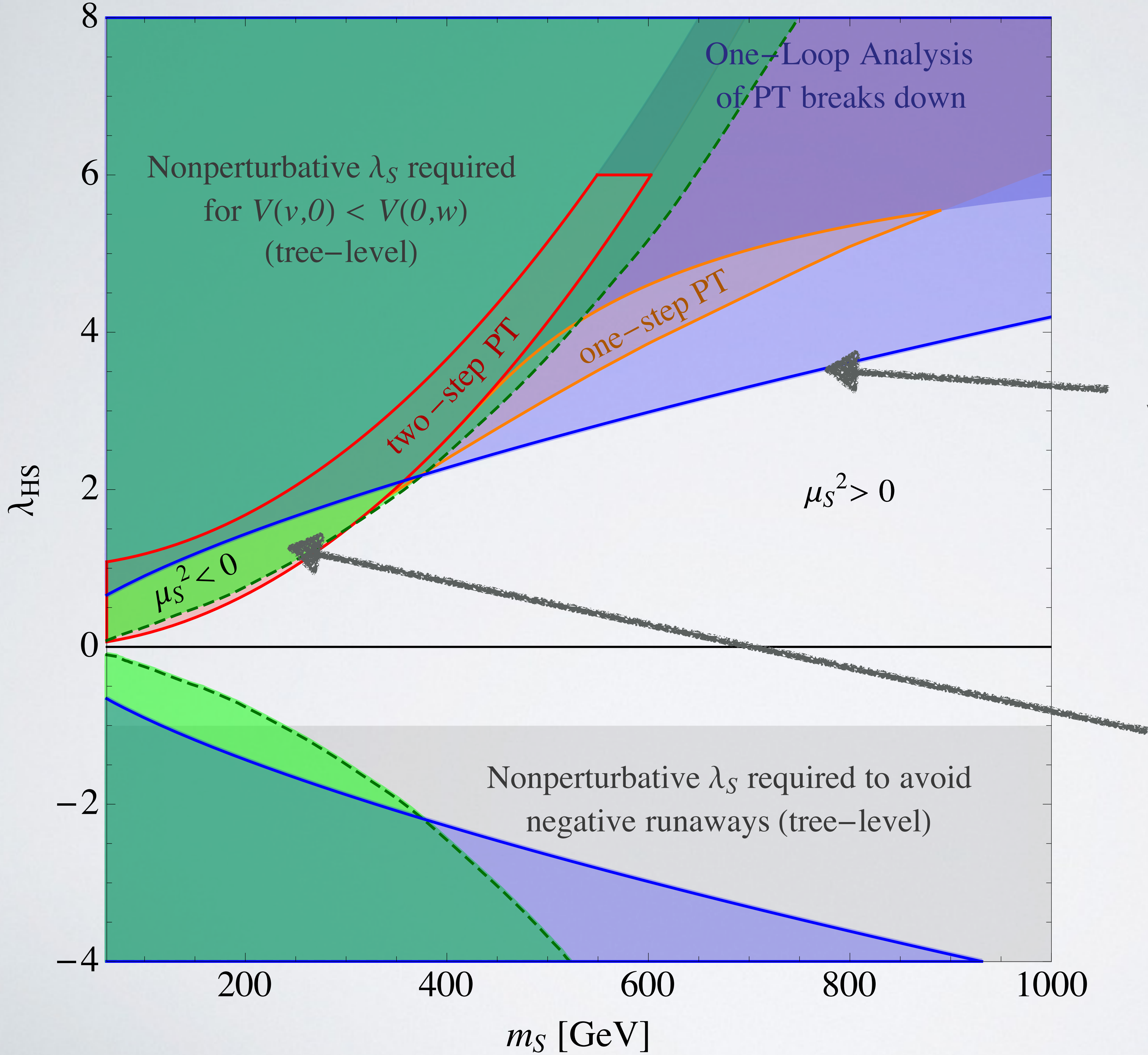


Figure 12. Dark matter properties of singlet scalar S, assuming it is a stable thermal relic. **Left**: magenta contours show contours of $\log_{10} \frac{\Omega_S}{\Omega_{\rm CDM}}$. In practically all of the parameter space viable for EWBG, the singlet scalar is a subdominant dark matter component. **Right**: green contours show the singlet scalar's direct detection cross section rescaled with relic density, $\log_{10} \left(\frac{\Omega_S}{\Omega{\rm CDM}} \times \sigma_S^{\rm SI}\right)$. The singlet-nucleon cross section is in units of $\rm cm^2$. The dark green shaded region is excluded by LUX [106]. The light green shaded region can be probed by XENON1T [107].

SUMMARY OF REGIONS



2 Sigma Exclusion with triple Higgs at 100 TeV

Collider

$$\frac{S}{\sqrt{B}} > 1$$

for 100 TeV

CONCLUSIONS

- EWBG provides a potential no-lose theorem for future colliders to test - Everything is tied to a low scale!
- We've explored a "nightmare scenario" for testing the EWPT of EWBG and although you will NEVER see it at the LHC, you CAN see it with a 100 TeV pp machine!!
- Higgs Factory not as important as 100 TeV! (at least for this)

BACKUP SLIDES